Advance the development of batteries to enable a large market penetration of hybrid and electric vehicles.

Program targets focus on enabling market success (increase performance at lower cost while meeting weight, volume & safety).

### Battery R&D Objectives

<table>
<thead>
<tr>
<th>Year</th>
<th>Electric Drive Vehicle Sales</th>
<th>Total Light Duty Vehicle Sales</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HEV</td>
<td>PHEV &amp; EV</td>
</tr>
<tr>
<td>2009</td>
<td>290,273</td>
<td>–</td>
</tr>
<tr>
<td>2010</td>
<td>274,648</td>
<td>345</td>
</tr>
<tr>
<td>2011</td>
<td>266,501</td>
<td>17,763</td>
</tr>
<tr>
<td>2012</td>
<td>434,648</td>
<td>53,169</td>
</tr>
</tbody>
</table>

### A Track Record of Success

DOE R&D has brought NiMH and Li-ion batteries into the automotive market

- **Nickelate technology** *(JCI)*: BMW, Mercedes.
- **Manganese technology** *(LG Chem, MI)*: GM Volt & Ford Focus EV.
- **Iron phosphate technology** *(A123Systems)*: Fisker, GM Spark.
Battery R&D Budget

<table>
<thead>
<tr>
<th>Battery/Energy Storage R&amp;D Funding ($, M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY 2012*</td>
</tr>
<tr>
<td>FY 2013**</td>
</tr>
<tr>
<td>FY 2014*** (request)</td>
</tr>
</tbody>
</table>

*FY 2012 SBIR/STTR removed.
**FY 2013 full year CR inclusive of SBIR/STTR.
*** FY 2014 budget request inclusive of SBIR/STTR.

FY 2013 Energy Storage R&D Budget** ($88M)

- **Exploratory Materials Research**: 32%
- **Funding Opportunity Announcement**: 23%
- **Battery Development**: 30%
- **Advanced Cell Development**: 15%
VTO Battery R&D Activities

**Advanced Battery Materials Research**
- Capacity Improvement
- Failure Mitigation

**Cell Design & Electrochemistry Optimization**
- Power & Capacity Increase
- Life Improvement

**Advanced Battery Development**
- Performance Optimization
- Cost Reduction

**Battery Materials**
- Advanced Anodes (600 mAh/g)
- Advanced cathodes (300+ mAh/g)
- Next Generation Electrolytes (5 volt)

**Cell Targets**
- 400Wh/kg
- 600Wh/l
- 5,000 cycles

- 2 – Electrode and Cell Fabrication
- 3 – Performance & Aging
- 4 – Scientific Diagnostics and Analysis

- 10-100 mAh cells
- 0.5 - 1.0 Ah cells
- 5 - 40+ Ah cells

- EM of Li$_2$FeSiO$_4$/C nanospheres

- Cost: $125/kWh
- Performance: 250 Wh/kg
- Energy Density: 400 Wh/l
- Power Density: 2,000 W/kg
Battery R&D Progress

- Current cost estimates (for a PHEV battery) average $485/kWh of useable energy.
- Cost projections are derived by the manufacturer using the USABC’s battery manufacturing cost model
  - For a production volume of 100,000 batteries per year.
  - For battery cell and module designs that meet DOE/USABC system performance targets.
  - Validated using established test procedures.
- Proprietary details of the designs and the cost models are presented at Quarterly Progress Reviews.

Progress of Battery Development Projects

Plug-In Battery Cost (per kWh of Useable Energy)

- 2008: $1,000 - $1,200
- 2010: $700 - $950
- 2012: $485
- 2014: Goal = $300
- 2016
- 2018
- 2020
- 2022: Goal = $125


### Battery Technology Comparison

#### 2012
- $/kWh: <600
- Wh/kg: <100
- Wh/l: <200
- W/kg: 400

#### 2022
- $/kWh: 125
- Wh/kg: 250
- Wh/l: 400
- W/kg: 2,000

**4X Cost Reduction**
- **2X Size Reduction**
- **>2X Weight Reduction**
Research Roadmap for 2015 & Beyond

Current Technology

- Graphite/Layered, Spinel, or olivine cathode

2014 Goal: $300/KWh

2015

- Silicon or Metal Alloy /High-V cathode

2022 Goal: $125KWh

2020

- Lithium Metal/Li Sulfur/ Li-air or Non lithium

New Battery Concepts

Graphite/High-Voltage cathode

Demonstrated $485 / kWh Useable in 2012
## Current Results

**Demonstrated Attributes of Battery Technologies**

<table>
<thead>
<tr>
<th>Maturity</th>
<th>Battery Performance (Pack Level)</th>
<th>Abuse Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specific Energy (Wh/kg)</td>
<td>Energy Density (Wh/l)</td>
</tr>
<tr>
<td><strong>Lithium-ion (current status)</strong></td>
<td>Pack</td>
<td>50-80</td>
</tr>
<tr>
<td><strong>Lithium-ion (future generations)</strong></td>
<td>Cell 20Ah+</td>
<td>155</td>
</tr>
<tr>
<td><strong>Lithium metal polymer (solid)</strong></td>
<td>Cell 10Ah+</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lithium metal / Sulfur</strong></td>
<td>Cell (Lab)</td>
<td>250-400</td>
</tr>
<tr>
<td><strong>Lithium metal / Air</strong></td>
<td>Lab Devices</td>
<td>400-600(?)</td>
</tr>
</tbody>
</table>
Accomplishments:

- **USABC EV battery development project**
  - Pack Level Gravimetric energy density (155 Wh/kg).
  - Pack Level Volumetric energy density (205 Wh/l).
  - Power density exceeds USABC targets.

- High confidence in meeting the cycle life target of 1,000 cycles.
  - Showing 97% capacity retention after 500 cycles.

- Demonstrated that cells can operate over a wide temperature window
  - -40 °C to 50 °C
Manufacturing Cost Reduction in Lithium-ion Batteries

Accomplishments:

- Demonstrated novel cathode slurry processing techniques (paste mixing & dry compounding)
  - N-Methylpyrrolidone (NMP) plays an active role in reactions, i.e. polymerization—high cap-ex and recovery costs.
  - Reduced NMP solvent use by 32%.
  - Increased coated electrode density by 31%.
- On path to increase cell energy density by 36%.
  - from 275 Wh/L to 375 Wh/L.
- On a path to reduce cell costs by 40%
  - from $420/kWh to $250/kWh.

<table>
<thead>
<tr>
<th>Trial Results</th>
<th>Solvent Used</th>
<th>Slurry Density</th>
<th>Electrode Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Standard</td>
<td>Standard</td>
<td>Standard</td>
</tr>
<tr>
<td>Powder Compounding</td>
<td>-31.9%</td>
<td>+22.9%</td>
<td>+31.4%</td>
</tr>
<tr>
<td>Paste Mixing</td>
<td>-24.3%</td>
<td>+14.5%</td>
<td>+15.2%</td>
</tr>
</tbody>
</table>

Slurry & electrode density improvement as a function of the processing approach
Accomplishments:

- Key materials account for 45-70% of total PEV pack cost.
  - The cathode accounts for 30% of key materials cost.
- VTO supported BASF to lower NCM cathode cost through precursor improvements & process modifications.
- NCM 111, 523, and 424 in production
  - NCM 424 (LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2) with 40% less cobalt (vs. standard NMC) yields lower cost (~15% reduction).
- High-Energy HE-NCM in R&D stage (260 mAh/g)
  - $4.8/kWh vs. $11.6/kWh (NMC): a potential 60% reduction in material production cost.
A New Synthesis Approach to Mn-rich Cathodes

- $0.5\text{Li}_2\text{MnO}_3 \cdot 0.5 \text{LiMn}_{0.5}\text{Ni}_{0.5}\text{O}_2$ cathode shows high capacities of ~250 mAh/g at low rates, and ~200 mAh/g at ~1C rate.
  - synthesized via a Li$_2$MnO$_3$ precursor

- The voltage profiles quickly stabilize with respect to the initial 10 cycles.

- This material displays good stability and capacity retention over extended cycling to high voltage.

Rate data of a Li$_2$MnO$_3$-based $0.5\text{Li}_2\text{MnO}_3 \cdot 0.5\text{LiMn}_{0.5}\text{Ni}_{0.5}\text{O}_2$ Cathode.

Stability of voltage profiles (at 15 mAh/g).
NanoSys is developing a graphite/Si composite anode material (SiNANOde™).

- SiNANOde™ target capacity is 700~1,000 mAh/g, and >800 cycles.
- Approach: Improve stability and SEI formation through an innovative surface modification of the Si nanowire anode coupled with an optimized electrolyte and binder chemistry.
- Demonstrated 850mAh/g of reversible capacity for SiNANOde.
- Demonstrated cycle life of ~500 cycles at 83% capacity retention at 0.3C cycling in half cells.

500 cycles of Si half-cell using NanoSys SiNANode material.
Computer Aided Engineering

AutoLion™

STAR-CCM+

sensor system for detecting & pre-empting short circuits inside a Li-ion cell.

Thermal contours at t=500 seconds under cold-start discharge.

Example module using 42 cells (Courtesy: Automotive Simulation Centre, Stuttgart, Germany).

Simulations results (from a validated FEA model) showing the effect of the cell format on thermal runaway following an internal short.
Recovery Act: Battery Manufacturing

On Going
- **Johnson Controls**: cell production and pack assembly at in Holland, MI
- **General Motors**: battery pack assembly at Brownstown, MI
- **LG Chem**: cell & pack capability in Holland, MI
- **SAFT**: cell production at Jacksonville, FL

Completed
- **A123 Systems**: cell production & pack assembly in Livonia & Romulus, MI
- **EnerDel**: cell production & pack assembly at Fishers & Mt Comfort, IN
- **Dow Kokam**: cell production & pack assembly capability in Midland, MI
- **Exide**: advanced lead acid battery production established in Columbus, GA
- **East Penn**: advanced lead acid battery production established in PA
## Recovery Act: Battery Manufacturing

### Materials Production

<table>
<thead>
<tr>
<th>On Going</th>
</tr>
</thead>
<tbody>
<tr>
<td>TODA: cathode production</td>
</tr>
<tr>
<td>Rockwood Lithium (formerly Chemetall Foote): lithium hydroxide production</td>
</tr>
<tr>
<td>HTTM: cell hardware production</td>
</tr>
<tr>
<td>BASF-Novolyte: electrolyte equip installd</td>
</tr>
<tr>
<td>Toxco: Recycling facility constructn comp</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASF: cathode production</td>
</tr>
<tr>
<td>EnerG2: anode production</td>
</tr>
<tr>
<td>FutureFuel: anode production</td>
</tr>
<tr>
<td>Pyrotek: anode production</td>
</tr>
<tr>
<td>Celgard: separator production</td>
</tr>
<tr>
<td>Entek: separator production</td>
</tr>
<tr>
<td>Honeywell: Li-salt pilot plant operational</td>
</tr>
</tbody>
</table>
Improvements in Cell Chemistry, Composition, and Processing

- Focus on the development of high energy Li-ion couples that can meet the cell performance and life targets: 400-600 Wh/l, 1200-1600 W/l, 1000-5000 cycles, etc.

Computer Aided Engineering for Electric Drive Batteries

- Dramatically improving the computation efficiency of current CAE Tools, or developing models capable of predicting the combined structural, electrical, and thermal responses to abusive conditions, and/or improving the accuracy of advanced life prediction.

Advanced Electrolytes for Next-Generation Lithium Ion Chemistries

- Advanced electrolytes that can enable the commercialization of next generation lithium ion technologies including silicon, tin or other high-energy alloy anodes and high voltage and high capacity cathodes, such as the 5 Volt Ni/Mn spinel or the Li-rich layered/layered transition metal oxides.
FY2014 Potential Funding Opportunities

Subject to Federal Budget Appropriations

- Advanced Battery Development (Cooperative Agreement)
  - RFPI on High Energy Battery Development
- Incubator (Start-Up: “On-Ramping Off-Roadmap Technologies”)
- VTO Program Wide FOA
  - Beyond Lithium Ion
    - Materials Processing and Production Improvements
- BATT (Solid Electrolytes: Exploratory Materials)
- SBIR
QUESTIONS?

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David.Howell@ee.doe.gov